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Coastal Sea Levels During the January 1988 Storm off the Californias

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INTRODUCTION

COASTAL SEA LEVELS play a key role in determining the magnitude and extent of coastal damage during storms. On open coasts such as those of the Californias, ocean waves provide the destructive power as well as much of the set-up that erodes beaches and overtops and floods coastal structures. However, the elevation of mean sea level, the tide and storm surge largely determine the degree of damage that waves can inflict on the shoreline. This was dramatically demonstrated during the highly destructive El Niño winter of 1982-83 when over $100 million of coastal damage occurred.[5]

On 16 to 18 January 1988, a remarkable winter storm approached and collided with the coasts of California and Baja California (Figure 1). Cayan et al.[1], as well as the other papers in the present volume, discuss the meteorology of this event as well as the pattern of damage on the California coast. We will show that were it not for some fortuitous conditions, the damage could have been much worse. The purpose of this paper is to examine the details of the coastal sea level related to this storm, and to describe how the different contributing factors varied along the coast and in time. Hourly data from 7 coastal tide gauges from San Francisco to San Quentin (Figure 1) have been analyzed for this study. We conclude from this and other work that we should be able to enhance the possibility of short-term warnings of coastal damage, using readily available information.

LARGE-SCALE CONDITIONS

Large-scale conditions in and over the Pacific Ocean are highly relevant to sea level along the west coast of North and South America. In southern California the annual sea level cycle is dominated by ocean surface temperature, with a small effect due to mean atmospheric pressure.[8] At La Jolla, this steric cycle is about 15 cm in amplitude, and is lowest in April (coldest water) and highest is September (warmest water). Steric heights in summer and winter are close to long-term mean sea level.[4]

High sea levels are a common manifestation of El Niño-Southern Oscillation episodes.[2,4] These long-term events are related to the relaxation of the westward blowing trade winds, as well as to a decrease in atmospheric pressure over the eastern tropical Pacific, as compared with the western Pacific. El Niño conditions tend to recur every four to seven years, with four or five strong events per century. These large-scale conditions, including the shifts in mean sea levels, were in a state of transition during January 1988. A moderate El Niño, present during 1986 and 1987, was breaking down and atmospheric pressure and wind pattern anomalies were reversing. The commonly cited *Southern Oscillation Index*, whose negative values are indicators of El Niño conditions, is formed with the normalized differences of sea level pressure anomalies at Tahiti and at Darwin, which are shown in Figure 2. The months of December 1986, 1987, and 1988 are indicated on the figure as A, B, and C. The index shows the El Niño of 1986-87 was forming at A, weakening at B, and reversing at C.

Large-scale sea level maps of the Pacific Ocean corresponding to those times display the effects of the El Niño cycle on sea level distribution (Figure 3). During an El Niño, sea level is high to the east and low toward the west, with typical sea level differences about 30 cm across the Pacific. During an anti-El Niño episode (Figure 3C), the exact reverse is true; positive anomalies are found in the extreme western Pacific, and negative anomalies are closer to the west coast of North America, as a result of the reversal of the atmospheric pressure deviations and of the strengthening of the trade winds. This translates into differences for the California coast between El Niño episodes and their counterparts, of about 10 to 20 cm in the position of mean sea level.

Figure 3B represents the conditions obtaining in late 1987 and early 1988. Although pockets of negative sea level deviations persisted in the western equatorial Pacific, conditions over most of the ocean were close to average. Specifically, sea levels along the west coast of the Americas were close to long-term mean values, and falling. The monthly average sea level at La Jolla during January 1988 was 83 cm above mean-lower-low water and nearly equal to the 1960-78 tidal epoch mean value.

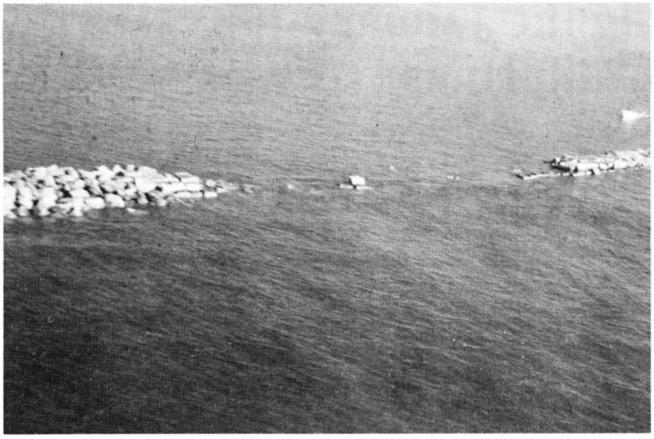

Figure 10. Breach in San Pedro Breakwater, Los Angeles - Long Beach Harbor.

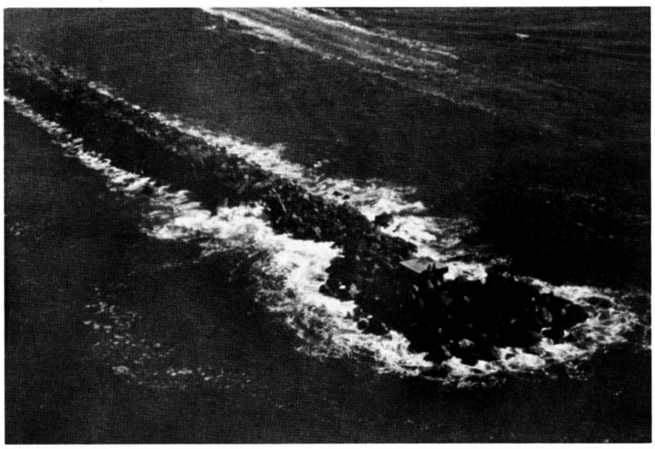

Figure 11. Damage to the head of the north jetty at Mission Bay, San Diego.

Figure 12. Loss of revetment at Mission Bay.

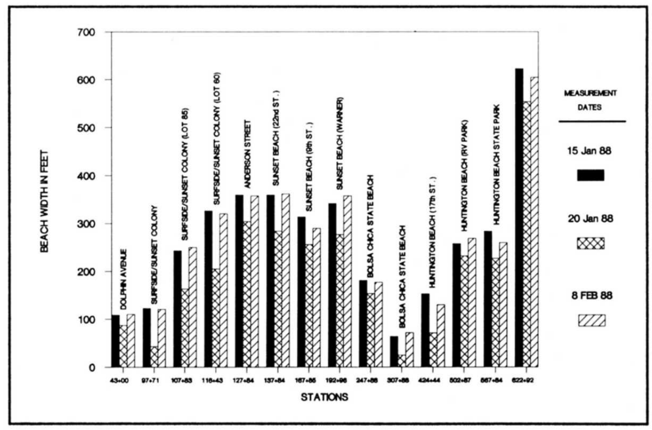

Figure 13. Beach width measurements.

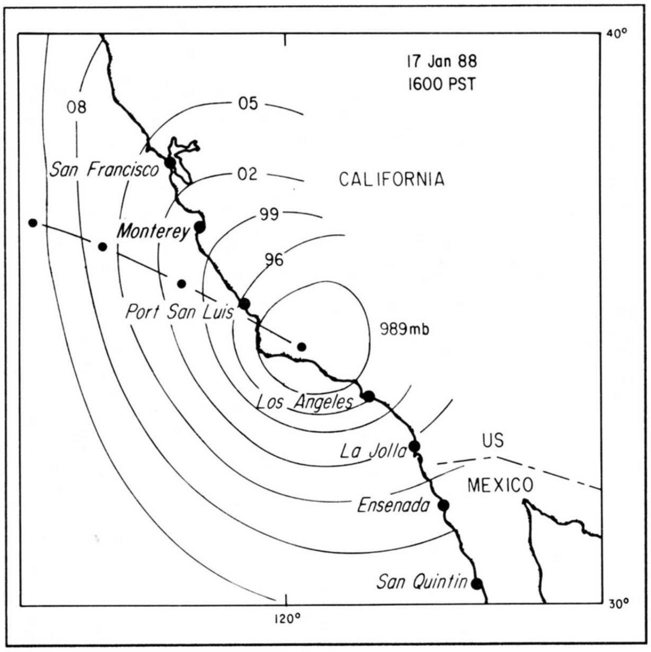

Figure 1. Map of the coast of the Californias showing location of the sea level stations and the storm approach path. Isobars show pressure pattern about the time storm made landfall at Avila Beach near Port San Luis.

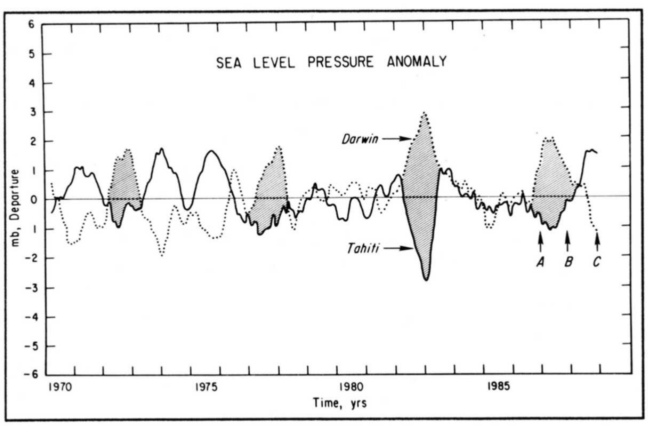

Figure 2. The *Southern Oscillation Index*, shown by five-month running means of sea level pressure anomalies at Darwin (dashed) and at Tahiti (solid). El Niño episodes are shaded (from Climate Diagnostics Bulletin, 1989).[3]

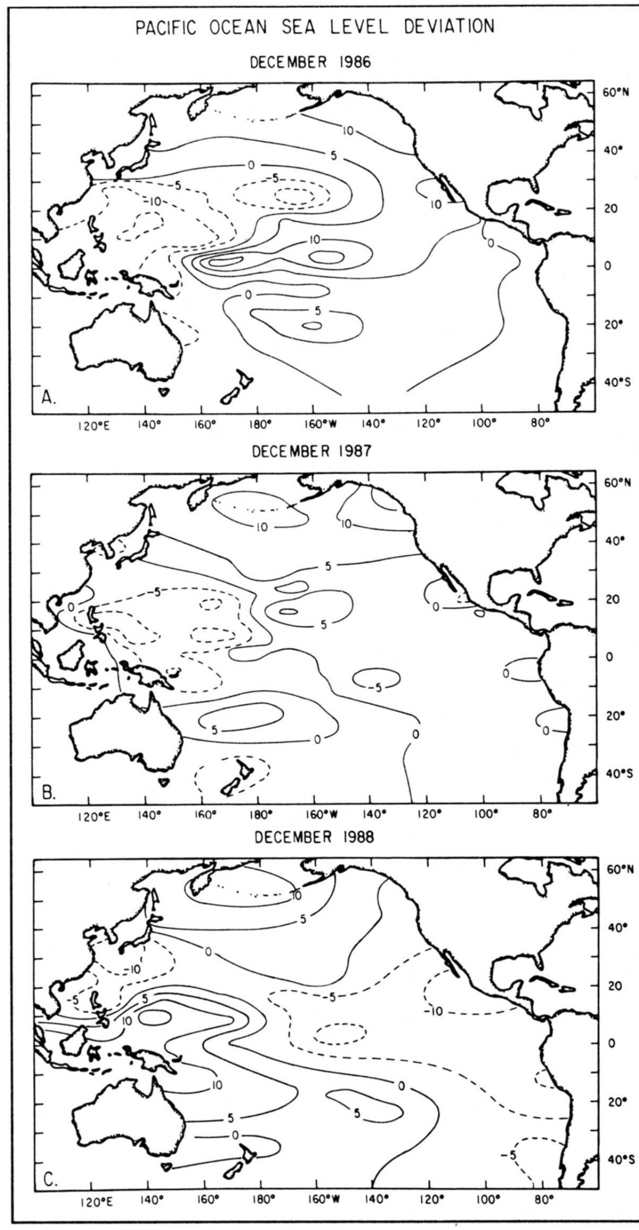

Figure 3. Monthly mean sea level distribution during December 1986 (A), December 1987 (B) and December 1988 (C) corresponding respectively to El Niño conditions, breakdown of the El Niño and reversal. Figures redrawn from Climate Diagnostics Bulletin; data supplied by Dr. Klaus Wyrtki.

THE TIDE

On the California and Baja California coasts, extreme tide ranges approach 3 m and exhibit a number of features relevant to the likelihood of coastal flooding. California's monthly predicted tidal extremes have only recently been tabulated and described.[9,10] The tide dominates sea level fluctuations on the west coast of North America. In this mixed tide region, a lunar day consists of two high and two low tides, each of different magnitudes. The lower-low typically follows the higher-high after about 7 or 8 hours. Partly because of this steep decrease, the tide remains near the maximum level, within 15 cm, for example, for about two hours. The rise from lower-low to the next higher-high requires the remainder of the tidal day, or about 18 hours. This aspect would have significance in limiting damage in southern California on 17 January 1988. During winter, higher-high water always occurs during the morning hours, often very early. In case of storm warnings, this timing can hinder preparations since these must be carried out at night.

Tidal variability during the lunar month is dominated by the spring-neap tidal cycle, with two periods each of relatively high ranges (springs) and low ranges (neaps). Spring tides coincide closely with the new and full moons, while neaps occur with waning and waxing half-moons. One spring tide each month is generally higher than the other, a consequence of monthly changes in lunar distance and declination. The declination cycle also influences the diurnal inequality.

Annual tide peaks occur in winter and summer, with as much as 60 cm higher monthly peaks compared with spring and autumn. The winter extreme is usually slightly higher than the summer due to the earth's closest approach to the sun, which occurs during the northern winter. The modulation itself is due to the declination of the sun, which is maximum in winter and summer and is another characteristic of the mixed-tide regime. The fact that the highest tides usually occur in the winter tends to enhance the effects of storm related sea level extremes. It also obscures the relatively small 15 cm annual cycle of steric mean sea level change, which is conventionally included in the predicted tide.

There is a substantial 4.4 year modulation of extreme tides resulting from progression of the lunar perigee past the equinoxes. This raises high tides roughly 15 cm. The cycle peaked in 1982-83, and contributed to the extreme flooding of that El Niño winter. The cycle also peaked in 1986–87, and will crest again in 1990–91. The winter of 1987–88 occurred near the mid-point of this modulation, with peak tides 6-9 cm below the highest extremes.

SEA LEVEL ON 16 TO 18 JANUARY 1988

The week of 15 to 22 January 1988 was scheduled to include the highest tides at all stations of the Californias, both of that month and of that year, with peaks on either 18 or 19 January.[9] Figure 4 shows the predicted tide (thin line) and the storm surge (thick line) over the 2-week period from 11–24 January at 7 locations from San Francisco to San Quintin (Figure 1). Tide predictions were prepared using standard harmonic constituents and subtracted from the respective sea level measurements to obtain the storm surge residual. The result was screened for errors and filtered[7] to obtain the smooth representation shown in Figure 4. It is clear that the overall timing of the mid-January storm surge event coincided closely with the peak tides. It is important to note that storm surge calculated from tide gauge records do not include the set-up due to breaking waves, since the gauges are frequently in water depths outside the surf zone, or in sheltered locations.

The peak surge amplitudes were large, but not record-setting.[6] The maximum value (plotted relative to long-term mean sea level at each location) occurred at Monterey around midday, 17 January and reached 30 cm. This is consistent with available weather charts that suggest record low barometric pressures around this time.[1] Peak values decrease both to the north and south, with relatively little surge (8 cm) at San Quintin. However, it is the timing and duration of the surge that is of primary interest. Peak tides and peak storm surge coincided only at San Francisco and Port San Luis and nearly coincided at Monterey (Figure 4). This occurred on the morning of 17 January when, for example, the high tide at Port San Luis exceeded the predicted value by 25 cm.

Flood damage on the central California coast from San Francisco south to Port San Luis was limited largely because coastal wave amplitudes were modest.[1] Significant wave heights along this reach were below 4 m until after about noon on 17 January when they began to increase sharply, reaching 9 or 10 m after midnight.[1] By that time, the tide was at the lower-high water stage, only about 30 cm above mean sea level at all stations, and about 90 cm below the higher-high of the morning. In addition, the storm surge dropped rapidly during the afternoon of 17 January. Residual sea levels eventually reached 15-20 cm below normal within a day or two at all stations, largely because of a strong high pressure system behind the storm system.[1]

Wave heights increased earlier from Pt. Conception south, reaching near peak values by early afternoon on 17 January.[1] The tides, however, at stations south of Pt. Conception were dropping sharply (Figure 4) at this time. The storm surge peaked during the evening while tides were either low or rising to the lower-high. By the time of the higher-high tide on the morning of 18 January, the storm surge had subsided to zero, or actually turned negative, while the wave heights were decreasing rapidly.

The major storm damage was concentrated at Redondo Beach where waves broke over the harbor breakwater on Sunday night, 17 January. The structural damage along the southern California coast would undoubtedly have been much more extensive had the storm passed over 12 hours earlier, or (especially) 12 hours later. The maximum storm surge amplitude at Los Angeles of around 25 cm would then have been added to the 120 cm tide.

Figure 4 shows that the timing of the storm surge maximum becomes progressively later to the south because of the storm approach path and coastline orientation. The tide peak, on the other hand becomes progressively later to the north due to the local tide regime. This propagation accounts for the increasing spread in time toward the south between the two peaks. The maximum storm surge at San Quintin was only about 8 cm, but occurred earlier than peaks farther to the north. This may be accounted for if the surge at San Quintin was mostly driven by frontal winds. This idea is consistent with available weather charts[1] which show frontal passage through the area around noon on 17 January.

Besides the timing of the storm, a second reason for the relatively limited extent of coastal damage was the short duration of this event. The average duration (over a 35-year record) for positive storm surge residuals at La Jolla is about 6 days.[6] This surge event only lasted 1 to 3 days, depending on location, and deteriorated rapidly as previously noted.

CONCLUSIONS

Storm surge during 16-18 January 1988 reached 25-30 cm along the coast of the Californias, ranking it in about the upper 10% of all tide residuals.[6] The duration of the storm surge and large ocean waves was relatively short compared with other severe storm episodes of comparable magnitude, notably 1982-83. The coast was spared much more widespread and severe damage largely because of the fortunate relative timing of peak high tides, storm surge, and wave attack, and the existence of average, background, mean sea level conditions.

The storm hit San Francisco about half a day before it hit Ensenada, and as the storm progressed, it should have been possible to provide sufficient warnings along the coast in time to alert the fleets in the various ports. Local weather reports on the west coast do not routinely include average sea level or expected storm surge conditions. The times and heights of high and low tides and the wave period and breaker heights, on the other hand, are often printed and broadcast, especially during storm periods. As Figure 4 illustrates, this may not be adequate, as the continuous tide curve is much more useful in estimating the potential coincidence and severity of a high tide and a storm surge (and large waves).

The essential elements for calculating useful, near real-time, west coast sea level heights and forecasts exist. Large-scale background monthly sea level heights are routinely circulated.[3] Storm surge models exist that use atmospheric pressure and wind predictions (measurements) to produce water level forecasts (hindcasts).[4,7] Real-time access to NOAA tide gauge data is now possible at six west coast stations, incuding La Jolla and San Francisco. Simple tide prediction computer routines are readily available and these could be used to compute surge in real-time. Combining these resources to produce near real-time, total sea level heights and forecasts seems relatively straightforward. Together with existing weather service wave forecasts, dissemination of these products could perhaps significantly reduce the level of damage during future storms along the coast of the Californias.

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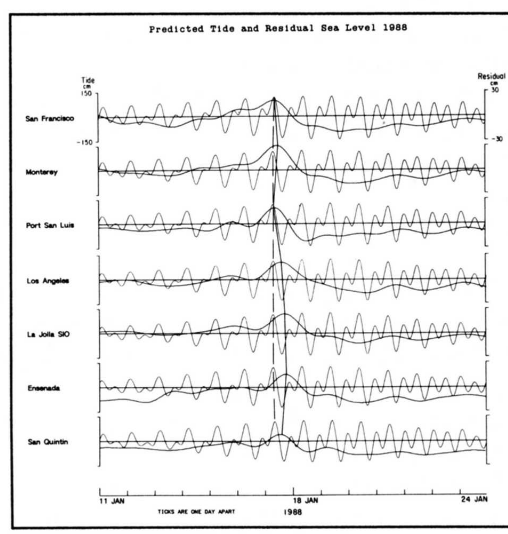

Figure 4. Predicted and residual sea level signals from selected tide stations along the coast of the Californias. Note that tidal phases propagate northward (dashed line), while storm surge peak generally progresses southward (solid line), following storm track.